Modified Atmosphere Packaging

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Introduction: Modified-atmosphere packaging (MAP) of fresh fruits and vegetables refers to the technique of sealing actively respiring produce in polymeric film packages to modify the O_2 and CO_2 levels within the package atmosphere. It is often desirable to generate an atmosphere low in O_2 and/or high in CO_2 to influence the metabolism of the product being packaged, or the activity of decay-causing organisms to increase storability and/or shelf life. For some products, modifying both O_2 and CO_2 may be desirable, and indeed, altering the O_2 level automatically alters CO_2 level. In addition to atmosphere modification, MAP vastly improves moisture retention, which can have a greater influence on preserving quality than O_2 and CO_2 levels. Furthermore, packaging isolates the product from the external environment and helps to ensure conditions that, if not sterile, at least reduce exposure to pathogens and contaminants.

MAP was first evaluated in the mid-to-late 1940's for its ability to reduce O_2 levels sufficiently to slow the ripening of apple fruit. The primary limitation of MAP application in the early studies was technical in nature; specifically, the lack of consistent control of O_2 levels in the package. Since then, the types and properties of polymers have increased to provide a wider range of gas permeability, tensile strength, flexibility, printability, and clarity. As a result, successful MA packaging systems have been developed for a number of commodities.

It is important to recognize that while atmosphere modification can improve the storability of some fruits and vegetables, it also has the potential to induce undesirable effects. Fermentation and off-flavors may develop if decreased O_2 levels cannot sustain aerobic respiration (Kays, 1997). Similarly, injury will occur if CO_2 exceeds tolerable levels. Ranges of non-damaging O_2 and CO_2 levels have been published for a numbers of fruits and vegetables (Kader, 1997a; Kupferman, 1997; Richardson and Kupferman, 1997; Saltveit, 1997; Beaudry 1999, 2000), minimally processed products (Gorny, 1997), and flowers and ornamentals (Reid, 1997). Horticultural crops differ in their tolerance for O_2 (Table 1) and CO_2 (Table 2). The range of O_2 and CO_2 levels for fruits (Fig. 1) and vegetables (Fig. 2) can overlap, or be distinct.

Table 1. O_2 limits below which injury can occur for selected horticultural crops held at typical storage temperatures. Data are from Beaudry (2000), Gorny (1997), Kader (1997a), Kupferman (1997), Richardson and Kupferman (1997), and Saltveit (1997). Those commodities in *italics* are considered having very good to excellent potential to respond to low O_2.

O_2 (%)	**Commodities**
< 0.5	*Chopped greenleaf, redleaf, Romaine* and *iceberg lettuce*, spinach, sliced pear, *broccoli*, mushroom
1.0	Broccoli florets, chopped butterhead lettuce, sliced apple, Brussels sprouts, cantaloupe, cucumber, crisphead lettuce, onion bulbs, apricot, avocado, *banana*, cherimoya, atemoya, sweet cherry, cranberry, grape, *kiwifruit*, litchi, nectarine, peach, plum, rambutan, sweetsop
1.5	*Most apples, most pears*
2.0	Shredded and cut carrots, artichoke, *cabbage*, cauliflower, celery, bell and chili pepper, sweet corn, tomato, blackberry, durian, fig, mango, olive, papaya, pineapple, pomegranate, raspberry, strawberry
2.5	Shredded cabbage, blueberry
3.0	Cubed or sliced cantaloupe, *low permeability apples and pears*, grapefruit, persimmon

4.0	Sliced mushrooms
5.0	Green snap beans, lemon, lime, orange
10.0	Asparagus
14.0	Orange sections

Table 2. CO_2 partial pressures above which injury will occur for selected horticultural crops. Modified from Herner (1987), Kader (1997a), and Saltveit (1997).

CO_2 (kPa)	**Commodity**
2	Lettuce (crisphead), pear
3	Artichoke, tomato
5	Apple (most cultivars), apricot, cauliflower, cucumber, grape, nashi, olive, orange, peach (clingstone), potato, pepper (bell)
7	Banana, bean (green snap), kiwi fruit
8	Papaya
10	Asparagus, Brussels sprouts, cabbage, celery, grapefruit, lemon, lime, mango, nectarine, peach (freestone), persimmon, pineapple, sweet corn
15	Avocado, broccoli, lychee, plum, pomegranate, sweetsop
20	Cantaloupe (muskmelon), durian, mushroom, rambutan
25	Blackberry, blueberry, fig, raspberry, strawberry
30	Cherimoya

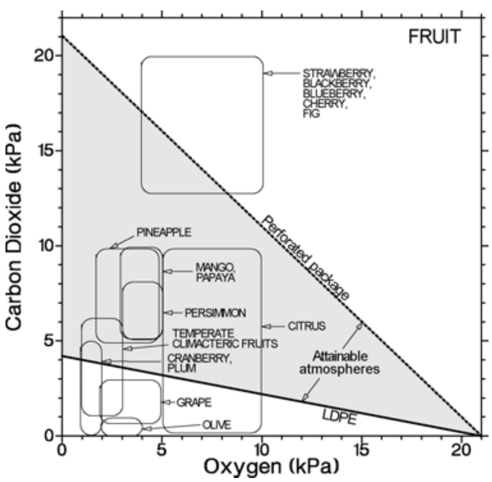

Figure 1. Recommended O_2 and CO_2 combinations for the storage of fruit. The shaded area depicts atmospheres theoretically attainable by MAP by film permeation alone (low density polyethylene, LDPE, lower boundary) and via perforations alone (upper, dashed line) or their combination shaded area). Data are adapted from Kader (1997). Reprinted from R. Beaudry, copyright 1999, pp. 293-303, with permission from Elsevier Science.

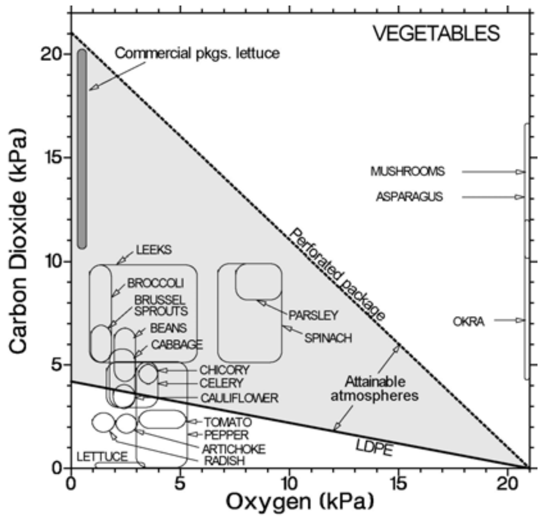

Figure 2. Recommended O_2 and CO_2 combinations for the storage of vegetables. The shaded area depicts atmospheres theoretically attainable by MAP using low density polyethylene (LDPE, lower boundary) and perforated packages (upper, dashed line) as redrawn from Mannapperuma et al. (1989). The darkened area represents atmospheres observed in commercial MA packages of mixed lettuce-based salads (Cameron et al., 1995). Reprinted from R. Beaudry, copyright 1999, pp. 293-303, with permission from Elsevier Science.

The composition of the atmosphere within a package results from the interaction of a number of factors that include the permeability characteristics of the package, the respiratory behavior of the plant material, and the environment. The films making up the package are selected to have specific permeability characteristics, and changes in these characteristics over time, temperature, and humidity follow known physical laws. The environment can be controlled to provide specific conditions. In contrast to these known and controllable factors are the often unknown and uncontrollable responses of the plant material. The plant specie, cultivar, cultural practices, stage of development, manner of harvest, tissue type, and postharvest handling all contribute and influence the response of the material to the generated atmosphere. The scope of plant responses can be further modified by initial gas flush of the package before sealing and inclusion of chemical treatments to slow unwanted processes or reduce decay. Each of these components of the packaging process can be examined separately to better understand how each contributes to packaging strategies.

Package Parameters: Atmosphere modification in MAP requires actively respiring plant tissue and a barrier through which gas exchange is restricted. The reduced O_2 and increases CO_2 that results from tissue respiration creates gradients across the film barrier that provides the driving force for gas movement into and out of the package. The levels of O_2 and CO_2 within a package depend on the interaction between commodity respiration and the permeability properties of the packaging film and/or microperforations (Beaudry et al., 1992; Kader et al., 1997a).

Two strategies for creating film barriers exist. The first strategy employs continuous films that control movement of O_2 and CO_2 into or out of the package. The second strategy uses perforated films with small holes or microperforations as the primary route of gas exchange.

Continuous Films: The movement of O_2 and CO_2 is usually directly proportional to the differences in gas concentration across the film. Steady-state (constant) O_2 and CO_2 levels are achieved in the package when the O_2 uptake and CO_2 production by the product are equal to that permeating through the film, a situation that exists only when the respiratory rate is constant.

Perforated Films: The rate of gas movement through a perforated film is a sum of gas diffusion through the perforation and gas permeation through the polymeric film. Generally, total gas flow through the perforations is much greater than gas movement through the film. Gas transmission through microperforations has been modeled (Fishman et al., 1996). The rate of gas exchange through perforations in a film is so much greater than through continuous films that a 1-mm perforation in a 0.0025 mm (1 mil) thick LDPE film has nearly the same gas flux as a half a square meter area of the film. As might be surmised, perforated packages are more suitable for produce having a high O_2 demand.

Gas Exchange Properties of Continuous and Perforated Films: The relative permeability to O_2 and CO_2 differ substantially between continuous and perforated films and results in considerable differences in gas exchange behavior. In packages composed of continuous films, the permeability of the package to CO_2 is usually 2- to 8-times that of O_2 permeability. If the rate of O_2 uptake by the product is roughly the same as its production of CO_2 (the normal case unless fermentation is taking place), the CO_2 gradient will be much lower than the O_2 gradient. For example, low-density polyethylene (LDPE) has permeability to CO_2 that is 4 times that of O_2. In a LDPE package having a 10% O_2 steady state atmosphere, the CO_2 level could be calculated as (21 - 10%)/4 or 2.75% CO_2. (Air is comprised of 78% N_2, 21% O_2, and 0.03% CO_2.) For perforated films, the permeability to CO_2 is only 0.77 times that of O_2. As a result, in a package relying on perforations for gas exchange, CO_2 levels climb to roughly the same extent that O_2 levels decline (ie., the gradients are nearly equal) such that the sum of O_2 and CO_2 partial pressures is usually in the range of 18 to 20%. For any given O_2 level, therefore, the perforated package will have a considerably higher level of CO_2 compared to the continuous film package. To extend the example above, if a package were designed to have a 10% O_2 steady state atmosphere using perforations as the route of gas exchange, the CO_2 level would be 0.77 x (21 - 10%) or 8.8%, which is about 3-fold greater than in the continuous film package. The relative elevation of CO_2 in perforated film packages may be critically important in package design, if CO_2 is needed to help control decay or degreening.

MAP relying on a combination of perforation/permeation has features of both systems, with the attainable combinations of O_2 and CO_2 being in-between those of packages relying on permeation and those relying on perforations (Beaudry, 1999; Mannapperuma et al., 1989) (Figs. 1 and 2). The temperature sensitivity for permeation, and the permeability of O_2 and CO_2 is somewhere between those for perforated packages and continuous film packages.

Temperature is extremely important in package design, and continuous and perforated films differ in their response to temperature changes. The O_2 and CO_2 permeability of continuous films increases with temperature, while the diffusion of gases through perforations is extremely insensitive to temperature changes. For instance, O_2 permeation through LDPE can increase 200% from 0 to 15 °C, but the exchange of O_2 through perforations will increase only 11% across this temperature range.

Depending on the rates of respiration and transmission through the package, atmosphere modification can be achieved rapidly or relatively slowly. At low temperatures, atmosphere modification can take several days such that some package systems would not achieve steady-state conditions prior to the end of their shelf life. In many cases, purging the package atmosphere with CO_2, N_2 or a combination of gases is often desirable during filling and sealing to rapidly obtain the maximum benefits of MAP.

Respiratory Parameters: The maximal rate of respiration for most fruit and vegetable products undergoes a 4- to 6-fold increase from 0 to 15 °C (Beaudry et al., 1992; Cameron et al., 1994, 1995; Lakakul et al., 1999). This means that product respiration increases at two or three times the rate of LDPE permeability, and thirty times the rate of perforation permeability with increasing temperature. When respiratory demand for O_2 increases faster than O_2 permeation as temperature increases, O_2 levels decline and may pose a risk to product quality. This limits the usefulness of MAP in some situations.

Safe levels of O_2 and CO_2 are important for package design. A lower O_2 limit has been associated with onset of fermentation and accumulation of ethanol and acetaldehyde (Beaudry et al., 1992). Fermentation is linked to the development of off-flavors and/or tissue damage. Effect of temperature on lower O_2 limit has been measured for a number of commodities including whole apple, apple slices, blueberry, and raspberry. In each case, lower O_2 limit increased with temperature. Lower O_2 limits vary from 0.15% to 5% (Table 1) and are influenced by temperature, commodity and cultivar (Beaudry and Gran, 1993).

Integrating Package, Product, and Environment: Mathematical models can integrate the film permeability to O_2, CO_2 and H_2O, and the respiratory response of the commodity to O_2 (and, in some cases, CO_2) along with its lower O_2 limit and upper CO_2 limit (Beaudry et al., 1992; Cameron et al., 1994; Lakakul et al., 1999; Fishman et al., 1996; Hertog et al., 1998). These models enable the reasonably accurate prediction of package performance, ie., O_2, CO_2, and H_2O content in the package headspace, under a variety of environmental conditions prior to construction of the package. Additionally, they permit the identification of limiting features of the film, package design, and product and environment conditions. Models typically include temperature dependency, but can also be developed to predict effects of package volume, resistance to heat flow, and developmental changes in product physiology on headspace gases.

Predicting and Controlling O_2 and CO_2 Content: A model can be developed to predict the steady state concentration of O_2 in the package headspace. Steady-state models incorporating temperature effects on respiration and permeability have been published for many commodities. In addition, more complex dynamic models have been developed to account for temporal changes in package volume, product respiration and the humidity and temperature of the environment (Fishman et al., 1996; Hertog et al., 1998).

Package performance can be depicted in a number of ways. Perhaps the most instructive format is describing the effects of temperature on package O_2 levels. For example, a package was designed to produce low O_2 and high CO_2 levels for 100 g of apple slices at 0 °C (Lakakul et al., 1999). The practical O_2 limit was set 3-fold higher than the fermentation threshold to prevent variation in respiration and permeability from causing a reduction in package O_2 below the lower limit. If the package relied on perforations for gas exchange, it would undergo a rapid decline in O_2 by the time the package reached 6 °C (42.8 ºF). Films with higher temperature sensitivity would be less prone to risk fermentation. In this example, packages were designed to maintain aerobic O_2 levels at 15 °C, the highest temperature to which they would be exposed. The performance of the packages can then be predicted at lower temperatures likely to be encountered during storage. A package O_2 model can also be used to predict very specific package criteria. For instance, the 100 g of apple slices described above were in a container having a film area of 120 cm^2. Film thickness and composition with different permeability characteristics could be selected to protect against fermentation.

A package model can also be used to clarify the nature of the mismatch between the temperature sensitivity of O_2 uptake and O_2 flux through the film and denote methods to ameliorate this problem. One method would be to choose a film with permeability changes for O_2 similar to that of the respiration of the product, so if temperature increases, respiration and permeability of the film increase an equivalent amount.

Another solution to the MAP temperature problem is to develop a package system that senses either the environment or the physiological status of the enclosed product and responds by increasing the permeability to O_2 (Cameron et al., 1993). Such 'sense-and-respond' packaging is technically difficult to develop, and progress has only been conceptual at this time (Smyth et al., 1999). A third approach is to design packages to function at the highest temperatures typically encountered in the distribution and retail cool chain and, as far as possible, maintain control over the temperature of the packaged product, thereby adapting to the limitations imposed by the film. Most companies using MAP have adopted this simple solution. Generally, the lowest temperature feasible is maintained, since temperature has a much more significant influence on preserving quality than the application of low O_2 (Kays, 1997).

Variation in the respiration rate of the product and the variation in film or pore permeability can influence package design. Variation in product respiration and package permeability has been measured for broccoli and the effect on package O_2 modeled (Cameron et al., 1993). Cameron et al. (1993)

concluded that there is an estimable risk of the package O_2 falling sufficiently low to promote fermentation in any product. Packages should be designed to generate O_2 levels well above the lower limit to ensure aerobic conditions.

Products such as broccoli, mushrooms, leeks and others have very high rates of respiration, and most continuous films do not have the capacity to provide enough O_2 to avoid fermentation. Accordingly, there is commercial interest to develop films with high gas transmission rates. Films that have improved rates of gas transmission by virtue of their polymeric nature are often blends of two or three different polymers, where each polymer performs a specific function such as strength, transparency and improved gas transmission. Similarly, films can be laminated to achieve needed properties.

The plastic polymer can also be mixed with an inert inorganic material such as $CaCO_3$ and SiO_2 to generate micoporous films. Gas permeabilities can be manipulated by adjusting the filler content, particle size of the filler and degree of stretching. The average pore size ranges from 0.14 to 1.4 µm in diameter (Mizutani, 1989). Films using microperforations can attain very high gas transmission rates. The diameter of microperforation generally ranges from 40 to 200 µm and by altering the size and thickness of microperforations, gas permeability through a package can be altered to meet well-defined product requirements. Microperforated films have also been used to extend the storability of strawberries and nectarines (Meyers, 1985), leeks, asparagus, parsnips, cherry tomatoes and sweet corn (Geeson, 1988) and apple (Watkins et al., 1988).

Water Vapor: Plant tissues tend to lose moisture when the RH is below 99 to 99.5%. Generally, water loss results in visible wilting or wrinkling of the surface of most commodities when it exceeds 4 to 6% of the total fresh weight (Kays, 1997). Fortunately, most MAP films are relatively impermeable to water. The RH is very near saturation in most continuous or perforated films packages. A saturated atmosphere at 20 ºC (68 ºF) has only 2.1% H_2O, and most external environments are at 30 to 60% RH, yielding a water vapor gradient of ~ 1%. The O_2 gradient can be several-fold higher. Because of the small driving force and the rapid rate of release of water vapor from the product, perforations have a much greater effect on the O_2 level than on RH. Fishman et al. (1996) calculated that perforating a continuous film increased O_2 flow 40-fold more than it increased H_2O flow. Only four perforations were required to achieve near ambient O_2 levels, while 40 perforations only reduced RH to 95%.

Condensation on the inner surface of the film is a common problem with MAP. A drop of only 0.2 °C in the film temperature can result in condensation in a package with an internal RH of 99% at 10 °C. Cold storage rooms have temperature swings of several degrees, so condensation is possible in almost any MAP. Fortunately there are film surface treatments that result in droplet dispersion, so the condensing water forms a thin, uniform layer that is virtually invisible. Condensation could also be reduced in MAPs with the few commodities such as tomato that tolerate low humidity by including materials in the package that reduced the RH. Salts enclosed in permeable sachets can reduce humidity in MAPs of tomato fruit (Shirazi and Cameron, 1992). The possibility of using films with very high water permeability has been examined using mathematical models (Cameron et al., 1995). However, since the external humidity would be critical in maintaining the proper package RH, this approach would encounter the difficulty of maintaining a specific humidity level in shipping and storage environments.

Temperature Management: Product temperature affects storability more than any other factor. Pre-cooling and temperature maintenance during handling and shipping are critical in preserving quality. Temperature also significantly affects film permeability and thereby the O_2 and CO_2 content of the package. The elevated rate of respiration at high temperature could be used to rapidly establish the desired package atmosphere, but this would only be useful in the few situations in which it would be more important to rapidly establish the atmosphere than to slow physiological processes, eg., to reduce cut-surface browning. Cameron et al. (1995) calculated that at 25 ºC (77 ºF), a package of blueberry fruit could attain a steady-state atmosphere in less than 2 days, whereas it required approximately 20 days at 0 °C (32 ºF).

The temperature of the produce in the package is managed by circulating cool air around the outside of the package. The film and the headspace atmosphere are barriers to heat movement, prevent rapid cooling, and reduce the effectiveness of refrigeration. A ‘safe radius’ for the distance from the center of the package to the circulated air can be calculated based on the heat of respiration and the rate at which heat can be removed by the cooler air (Sharp et al., 1993). For instance, the center of a package of broccoli must have a radius of less than 14 cm to keep it within 1 °C of the refrigerated air. Slower respiring pear would function as well with a larger package having an effective radius of 50 cm.

Plant Responses to MAP: Some of the most important factors that affect shelf life of fresh horticultural products are ripening and/or senescence, decay, and cut surface browning. The effect of MA on these factors has been well characterized. The application of MAP to affect these limiting factors can be restricted for some crops by adverse and/or non-beneficial physiological responses; eg., induction of fermentation. Fresh product quality can be maximized more effectively by good temperature management than by atmosphere modification.

Ripening and Senescence: Low O_2 and elevated CO_2 can significantly reduce the rates of ripening and senescence primarily by reducing the synthesis and perception of ethylene (Burg and Burg, 1967; Abeles et al., 1992). Changes in respiration and starch, sugars, chlorophyll, and cell wall constituents during ripening and/or senescence can be reduced, and in some cases nearly arrested, by eliminating ethylene action through the use of low O_2/high CO_2 atmospheres.

Chlorophyll loss, a desirable trait for many climacteric fruits, results in quality loss for many vegetables Chlorophyll degradation during the senescence of green vegetables can be inhibited by low O_2 and elevated CO_2, a response that in some cases is partly mediated by ethylene, as with broccoli (Ku and Wills, 1999).

While low O_2/elevated CO_2 atmospheres are commonly used to minimize ethylene-dependent responses attendant to ripening in CA rooms, this goal may not be fully compatible with MAP. The problem with the incorporation of MAP for ripening control is not one of efficacy, but rather one of logistics. Modified atmospheres are most effective at reducing ripening prior to the onset of ripening, rather than at a later stage. However, packaged products are usually intended for immediate consumption by the consumer and an unripe product is not immediately edible or is of reduced quality relative to the ripe product. Thus, the advantage of improved shelf-life by retarding ripening runs counter to the needs of the consumer when retail MAP systems are used. Nevertheless, MAP can reduce the rate of ripening of some commodities such as tomato even during its later stages (Yang and Chinnan, 1988). More potential for using MAP to control ripening may exist at the packinghouse or distributor level as in the case of overseas shipment of apples (Watkins et al., 1998), rather than at the retail level.

Decay: Decay control is a particularly important problem for many crops. Levels of $> 10\%$ CO_2 effectively slow or stop the growth of numerous decay organisms (Brown, 1922). Low O_2 has a very limited effect on decay organism activity or survival at levels above the fermentation threshold of most commodities. While not all horticultural commodities can withstand CO_2 levels sufficient to inhibit fungal activity, a number of highly perishable commodities are not adversely affected (Table 2). Notable among these are strawberry, blueberry, blackberry, raspberry and cherry, which can be stored successfully under a CO_2 atmosphere of 10 to 20%.

Packaging strategies to enhance CO_2 include initial purging with high levels of CO_2. This strategy relies on continued respiration to replace CO_2 lost from the package, and is in commercial use for many berry crops. The choice of film type markedly alters the CO_2 content of a package. In particular, perforated and continuous films differ in their discrimination between O_2 and CO_2. The perforated films will generate a higher partial pressure of CO_2 for a given concentration of O_2 in the package. Perforated packages can accumulate CO_2 to levels within the fungistatic range. For example, a perforated package that generates 1% O_2 could accumulate a 15% CO_2 atmosphere.

While high RH reduces water loss, it also aggravates decay development. Strategies to reduce humidity in packages using salt sachets for the purpose of limiting decay have been explored (Shirazi and Cameron, 1992). A number of effective chemical additives can be used at various points during processing and packaging to reduce decay (see section on “Processing Aids”).

Cut Surface Browning: Most of low O_2 MAP is used to reduce the browning of cut surfaces on lightly processed products such as lettuce and salad mixes. Atmosphere modification is often used in conjunction with processing aids to retard brown color development (see section on "Processing Aids"). Smyth et al. (1998) demonstrated that O_2 levels below 2%, but above the fermentation threshold of ~ 0.5% reduced the rate of browning in lettuce. The partial pressure of O_2 in commercial packages of lettuce and salad products is often below the fermentation threshold (Cameron et al., 1995; Peiser et al., 1997). However, the fermentation of lettuce, if not severe, results in very few off-flavors (Smyth et al., 1998).

Negative Responses: Respiration is reduced as O_2 becomes limiting, but there is usually a limit to which O_2 can be reduced. The lower O_2 limit is frequently considered to be the level of O_2 that induces fermentation. This fermentation threshold is not always the lower O_2 limit in commercial practice, however, because lower O_2 levels may confer benefits that outweigh the loss in flavor or other quality parameters. Ethanol, acetaldehyde, ethyl acetate and lactate are products of fermentation that can contribute to the development of off-flavors as well as physical injury (Kays, 1997; Mattheis and Fellman, 2000).

Production of compounds that contribute to characteristic aromas of many fruit, including apple, banana, pear, peaches, strawberries and others, can be adversely affected by low O_2 and elevated CO_2 (Song et al., 1998; Mattheis and Fellman, 2000). Synthesis of aroma compounds are generally suppressed by high CO_2 and low O_2, in part by their action on ethylene perception, but also via action of O_2 on oxidative processes, including respiration required for substrate production. Most products recover from moderate low O_2 suppression of aroma volatile production and eventually develop characteristic flavors. However, low O_2 MAP may suppress aroma production so consumers perceive reduced quality upon opening the container.

Conclusion: A number of critical points need to be considered in package design and application:

1. Not all plant materials benefit from MAP. Those that do may differ in their responses to atmospheres generated.
2. Consideration should be given the factor most limiting to the delivery of a product to the consumer and the packaging strategy developed accordingly.
3. Reduction of water loss by packaging has a marked influence on storability. Elevated humidity prevents desiccation, but can also enhance decay.
4. Temperature control is of critical importance and, by itself, has a greater impact than atmosphere modification for most products. Temperature should be near the storage/shipping temperature as soon as possible after packaging except in those cases where a slightly elevated temperature is needed to assist in rapid atmosphere generation.
5. Heat transmission from product through the package, carton, and pallet stack needs to be considered in the development of handling procedures.
6. If a package is designed to produce low O_2 or high CO_2 levels at low temperatures, temperature > a few degrees above of the target temperature should be avoided or low O_2 injury may result.
7. Package modeling can improve understanding of how package, plant and environmental factors interact and can be useful in package design.

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